

Streamflow Forecast Errors and Their Impacts on Forecast-based Reservoir Flood Control

Zhao Liu¹ · Yiping Guo² · Lixia Wang³ · Qing Wang¹

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Abstract To make full use of water captured by reservoirs in flood seasons, methods such as forecast-based reservoir flood control (i.e., reservoir operation during flood periods based on precipitation or inflow forecasts) have been developed in China in the past few decades. The success of forecast-based reservoir flood control depends heavily on the precision of the precipitation or inflow forecasts. This study analyzes the sources of uncertainty and quantifies it in the process of reservoir flood control based on forecasts. First, flood inflow series is regarded as a random process with the forecasted flood inflows as its expectation process; the flood inflow error series, which is the difference between the observed inflow process and the forecasted inflow process, is obtained according to the statistical characteristics of the flood forecasts. Second, reservoir flood routing simulations are carried out using the Monte Carlo method with the flood inflow error series as an input to obtain output water level and discharge series. Finally, the frequency distributions of the maximum water level (MWL) reached during the passage of floods are used to evaluate the uncertainties and the corresponding risks associated with forecast-based flood control. These uncertainties and risks are what the operators of the reservoirs care about the most.

Keywords Water resources · Reservoir operation · Flood regulation · Uncertainties

1 Introduction

Under the influence of global climate change, the spatial and temporal distribution of rainfall has become more uneven. Droughts and floods occur more frequently, posing greater challenges to water resources utilizations. In China, with its rapid economic development,

✉ Zhao Liu
lz975315@yahoo.com

¹ Institute of Water and Development, Chang'an University, Xi'an 710054, People's Republic of China

² Department of Civil Engineering, McMaster University, Hamilton, ON, Canada L8S 4L7

³ College of Earth Sci & Resources, Chang'an University, Xian 710054, People's Republic of China

water resources are becoming increasingly scarce. At the end of the last century, research on reservoir flood regulations began shifting towards implementing “regulations based on forecasted information” which uses predicted information about watershed runoff in order to retain and utilize more volumes of water while incurring acceptable levels of risk. In essence, for forecast-based flood control, decisions regarding reservoir water storage or discharge are made in advance because there are lead times available due to the use of reliable inflow forecasts. With the construction and improvement of streamflow and rainfall monitoring systems, the accuracy of flood and rainfall forecasts has increased significantly, providing a necessary condition for the implementation of operations based on forecasts (Cheng and Chau 2004).

Previous studies demonstrated that, if deemed necessary in a forecast-based operation, changes in reservoir storage can be made in advance for water supply enhancement and electricity generation. The flood management benefits of forecast-based operation vary greatly between different river systems. The characteristics of potentially flooded areas, the outlet capacity of the dam and its downstream channel capacity are all important factors. A number of studies have been conducted to examine the pre-requirements, operating rules, and formulation of forecast-based reservoir flood regulation rules (Russell and Caselton 1971; Cardoso et al. 2009). As far as operating rules are concerned, many researches take ‘cumulative net rainfall’ in runoff yield calculations or ‘peak discharge’ in runoff hydrograph calculations provided by flood forecasts as an index of rules (Huang et al. 2001). There are advantages and disadvantages for each of these indices, and in practice, selection should be made on the basis of the specific reservoir and its current condition (Wang et al. 2006). For use as an index of rules, ‘cumulative net rainfall’ is more suitable for cases where rainfall is usually uniformly distributed throughout the contributing watershed, and the reservoirs have strong regulation capabilities or larger flood storage capacities. ‘Peak discharge’ focuses on the inflow rate rather than overall runoff, so it is more suitable for use as an index of rules for cases where rainfall may not be uniformly distributed throughout the contributing watershed, and the reservoirs are with limited flood storage capacities or regulation capabilities.

Taking the Biliuhe reservoir as an example, Zhai et al. (2006) formulated detailed forecast-based operating rules for flood control on the basis of flood classifications. Wasimi and Kitanidis (1983) discussed the real-time operation of a multi-reservoir system using linear quadratic Gaussian control method based on short-term forecasted information. Unver and Mays (1990) developed a model for the real-time optimal flood operation of river-reservoir systems within an optimal control framework. Application of the model is illustrated through a case study for Lake Travis on the Lower Colorado River in Texas, USA. Taking the Three Gorges Reservoir (TGR) as a case study, a dynamic control of the cautionary water level (cautionary water level refers to the water level that the reservoir is not allowed to exceed during flood seasons before the occurrence of any actual floods, sometimes it is also referred to as the limited water level) considering inflow uncertainties was proposed and developed by Li et al. (2010), the results show that it is effective in increasing hydropower generation and floodwater utilization without increasing flood risks.

As a matter of fact, relying on effective and highly accurate inflow forecasts, forecast-based reservoir flood control has advantages in improving flood water utilization as well as reducing flood risks. But these benefits all depend on the accuracy of the forecasts; therefore, forecast-based flood control must be founded on accurate precipitation and/or inflow forecasts. Based on the inflow forecast precisions and reservoir characteristics, Liu et al. (2011) proposed a forecast-based flood control methodology for the Ankang reservoir in Shaanxi, China, in

which forecasted runoff was selected as the index of operating rules, and the methodology was proved to be more effective in floodwater utilization than conventional operating procedures.

Furthermore, a large number of studies (e.g., Wilson and Kirdar 1970; Apel et al. 2004) indicate that it is extremely important to evaluate the risks encountered in applying forecast-based flood control rules. Zhang et al. (2011) discussed the dynamic control of the Dahuofang Reservoir in Liaoning, China and its risks under different flood forecast error levels. Diao and Wang (2010) considered uncertainties in hydrology, hydraulics and operator conduct and established a multifactor risk model for flood control using forecasted information. Jiang and Fan (2004) developed a stochastic model of flood routing in which the risk of hydrological forecasts is transformed into the risk in flood control, the results indicate that the improvement of the accuracy of hydrological forecasts can result in corresponding risk reductions.

While some researchers (e.g., Gôppert et al. 1998; Vrijling 2001; Fu et al. 2013) have developed mathematical models and engaged in discussions on the risks of forecast-based flood control, most researchers currently analyze these risks qualitatively. Due to the intrinsic complexity, risks encountered in reservoir flood control based on forecasted information are not well understood (Huang and Hsieh 2010). The uncertainty and risk evaluation for forecast-based operation is different from its traditional operation counterpart because of new risk factors and forecast errors, which play a significant role in the flood routing process. This is the main reason why forecast-based operation is still not extensively adopted for most of the reservoirs in China, including the Ankang reservoir.

Combining stochastic analysis and reservoir routing simulation, an uncertainty assessment scheme for forecast-based flood control is presented in this paper, this scheme also provides a practical solution for related risk-quantification problems. In addition, this research takes the Ankang reservoir as an example, the accuracy of the inflow real-time forecast system and the statistical characteristics of forecast errors are analyzed first. Secondly, using the Monte Carlo method, flood routing simulation is conducted according to the forecast-based operating rules incorporating forecast errors. Finally, the frequency distributions of the maximum water levels (MWLs) reached during the passage of floods are determined and their main features are identified and discussed. These additional results provide a strong support for the application of forecast-based operation of the Ankang reservoir.

2 Flood Routing Model and Inflow Forecast Error Series

The main risk factors encountered in reservoir flood regulations include the uncertainties about incoming floods, uncertainties about the initial water levels in the reservoir, uncertainties of discharge capacities, and possible operational delays. However, previous research (Feng et al. 2009) has shown that the hydrological uncertainties of incoming floods are the primary risk factors for reservoir flood regulations.

2.1 Conventional Flood Control Mode, Forecast-Based Flood Control Mode, and Uncertainty of Flood Flows

In the conventional operation with specified operating rules, the measured reservoir inflow at the current time is used to determine the exact operating rule to follow at the current time; whereas in forecast-based operations, this decision is made using forecasted inflow rates, runoff volumes or precipitation amounts. There is no doubt that predicted data will inevitably

contain errors. These errors can be defined as the amount of deviations of the forecasted inflows from the true reservoir inflow rates. The accuracy of forecasts directly affects flood regulations and then determines the subsequent levels of risk of dam overtopping. However, the information regarding the current reservoir inflow rates based on which conventional operation rules are formulated is not completely accurate either; in other words, the measured reservoir inflow rates are also inaccurate, some differences between the measured and the true values also exist. This is primarily reflected in the following three aspects. Firstly, the reservoir inflow rate is an instantaneous value which changes constantly and is difficult to measure. Even if the average reservoir inflow rate in a certain period of time can be calculated, the measurements is still inaccurate because the measured reservoir inflow rate is commonly obtained by using changes in water levels in a certain period of time. Therefore, the reservoir inflow rate on which flood regulations are based is obtained largely on the basis of the flow rate measurement of the upstream river and also the operators' experience. Secondly, the inflows into a reservoir itself are a vague concept and cannot be accurately defined because there may be multiple sources of inflows and some of them might not be identified and included. Thirdly, the floods and their waves change under the influence of boundary conditions. Even if the dynamic reservoir capacity is taken into consideration, the flow rate of floods into reservoirs and their effects cannot be completely described. Although the reservoir inflow rates cannot be accurately known during real-time operations, with the improvements in measurement technology and accuracy, the measured values can be very close to the true values, and can be used directly in practice.

The above analysis shows that both forecasted and measured data are unlikely to perfectly match actual reservoir inflow rates. This mismatch is generally referred to as the forecast errors, the measurement errors, or the uncertainties with respect to the reservoir inflow process. Even if the frequency of an incoming flood is known and is within the design limit of the reservoir, risk of dam overtopping may still exist because of the uncertainties of the exact flood flow process; or in other words, risk is caused by the uncertainties of forecasted or measured flow rates. If a forecast with detailed flow rates is assumed to be completely accurate, then uncertainty disappears and the risk of overtopping the dam during the passage of a flood within the design limit should approach zero.

2.2 Mathematical Model for Flood Routing Based on Forecasted Inflows

When evaporation, leakage and other losses are ignored, the mathematical model for flood routing can be presented as:

$$\begin{cases} Q_{in} - Q_{out} = \frac{dW}{dt} \\ W = f(Z) \\ Q_{out} = g(R, Z) \end{cases} \quad (1)$$

Where Q_{in} and Q_{out} are the inflow and outflow rates of the reservoir at time t respectively; Z is the water level of the reservoir; W is the storage of the reservoir which is determined according to the water level-storage relationship of the reservoir $f(Z)$; the outflow rate Q_{out} is determined based on the water level of the reservoir Z and the forecasted runoff depth R according to the forecast-based operating rule $g(R, Z)$. This model is comprised of the water balance equation, the operating rules, and the relationship between reservoir water level and storage capacity. Whether for conventional operations

or operations based on forecasts, the mathematical model of reservoir operation is solved on a time step-by-time step basis through an iterative process. This model takes measured or forecasted reservoir inflows as input and outputs the discharge flow rates and the reservoir water levels. The flow chart for uncertainty analysis considering forecast errors in forecast-based flood control is shown in Fig. 1.

The mathematic model of the reservoir operation itself is a deterministic model. That is, when the inflow process is a deterministic process, the output process is also a deterministic process. However, in real-time operations based on forecasts, the forecast values of the inflow rate or the amount of water in the reservoir at any moment has a margin of error and may be treated as random variables. During the entire flood routing process, a time series of errors of forecasted reservoir inflow rates is formed. This series is inputted into the flood routing model as a realization of a random process.

2.3 Inflow Real-Time Rolling Forecast and the Statistical Characteristics of Forecast Errors

To better understand the statistical characteristics of an inflow forecast series, it is necessary to take samples of forecasted values and compare them with actual inflows observed later on. In this study, data analysis of the forecast errors of reservoir inflows with various lead times was carried out by comparing the measured and forecasted reservoir inflow rates over ten floods that occurred at the Ankang reservoir in Shaanxi, China, the example reservoir used in this paper.

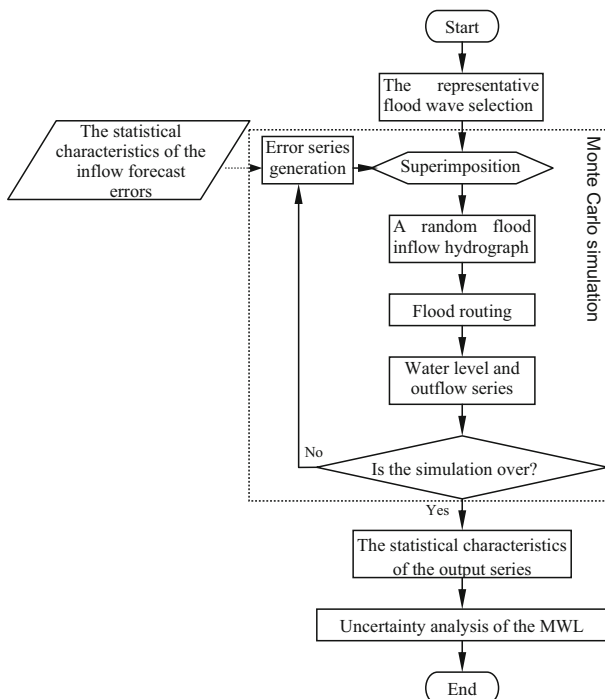


Fig. 1 The flow chart of uncertainties analysis for reservoir flood routing based on inflow forecasts

The reservoir inflow flood forecast system of the Ankang reservoir uses rolling forecasts. It forecasts once every hour and can forecast the flow rates within the next 24 h with a reliable forecast lead time of about 8 h. Since a 6-h lead time was used in the forecast-based flood control operating rules, we analyzed the forecast data within 6 h of the time of forecast. The forecast error at various lead times were calculated from measured and forecasted inflow data in order to obtain samples of forecast error series. The frequency distribution characteristics of the series of forecast error samples at different lead times were analyzed. Hypothesis testing indicated that the absolute errors of the forecasts at various lead times follow normal distributions. The mean and standard deviation of the distribution of the forecast errors at various lead times were obtained and are shown in Table 1.

According to the above analysis, the mean value of the error series of the flood forecasts for the Ankang reservoir varies within $\pm 100 \text{ m}^3/\text{s}$ and may be treated as zero compared to a minimum flow rate of $12,000 \text{ m}^3/\text{s}$ in the flood period; the standard deviation at various lead times differs and changes slightly, ranging from roughly 500 to $600 \text{ m}^3/\text{s}$. When the reservoir inflow rate is small, the absolute error of its forecast tends to be small and vice versa; therefore, strictly speaking, the forecast error series of the reservoir inflow is a non-stationary process. But it was noticeable that the mean and standard deviation of the forecast errors do not change very much with the change of lead times when the reservoir inflow rate exceeds $12,000 \text{ m}^3/\text{s}$. There is no obvious pattern of change of the mean and standard deviation of the forecast errors with respect to the change of the lead time. Therefore, if the inflows are greater than $12,000 \text{ m}^3/\text{s}$, it can be assumed that the statistical characteristics of the flow rate errors are the same for different lead times of interest. Furthermore, the statistical characteristics themselves also changed a little bit with the change of the size of the analyzed samples, in simulations, it is therefore not only inconvenient but also unnecessary to generate forecast error series strictly in accordance with the statistical characteristics listed in Table 1. In order to reasonably simplify the following analysis, the forecast error series of reservoir inflows are treated as a stationary random process. This means that when the reservoir inflow rate exceeds $12,000 \text{ m}^3/\text{s}$, the mean and standard deviation of the reservoir inflow forecast errors will not change with the change of lead times, with approximately $\mu=0$ and $\sigma=600\text{m}^3/\text{s}$.

3 The Ankang Reservoir and its Forecast-Based Flood Control

3.1 The Ankang Reservoir

As a reservoir with incomplete annual regulation capabilities, the Ankang reservoir is located upstream of the Han River in the southern part of the Shaanxi Province of China (Fig. 2). It is a

Table 1 Statistical characteristics of forecast errors with different lead times at Ankang reservoir

Statistic	Lead time						Forecasted runoff in 6 h (mm)
	1 h	2 h	3 h	4 h	5 h	6 h	
Expected value $\mu(\text{m}^3/\text{s})$	-57	38	56	-79	76	-92	0.0645
Standard deviation $\sigma(\text{m}^3/\text{s})$	568	582	548	623	525	584	2.06



Fig. 2 The location of the Ankang reservoir and Han River

multi-purpose reservoir mainly used for generating electricity, flood control, shipping, and tourism. With a total capacity of 3.2 billion m^3 and a maximum flood control capacity of 0.98 billion m^3 , the reservoir serves excellent flood control and eco-environmental functions. The dead water level of the reservoir is 300 m, the normal water level is 330 m, the cautionary water level in flood season is 325 m, and the maximum flood level is 337.33 m. The dam of the reservoir was designed to withstand floods of both 1000-year return period (design flood) and 10,000-year return period (check flood). The flood control standard for the Xiangyu railway upstream of the reservoir is 100-year flood, i.e., the water level in the reservoir cannot exceed 330 m when a 100-year flood occurs.

3.2 Precipitation and Flood Forecast Information Systems

The automatic operation system of the Ankang reservoir has the following primary functions and devices: real-time data collection and processing; receiving, displaying, and processing of satellite cloud images, monitoring, data acquisition and transmission equipment; voice query and alarm system, and hydrologic forecasting systems. The overall system is an integration of subsystems such as the Shiquan (a county within the region) hydrological data acquisition and transmission system, the Ankang hydrological data acquisition and transmission system, the upstream and downstream water level systems, satellite cloud images, and the weather station information systems. The 18 stations of the Shiquan hydrological data acquisition and transmission system including five rain gauge stations, nine stage/rain gauge stations, two stage gauge stations, and three relay stations are distributed between the Hanzhong City and the Shiquan County in an area of 12,400 km^2 . It was put into use in 1997. The satellite cloud image system collects a facsimile image of Japan's GSM-5 satellite once every hour and is connected with the local area network. It was put into use in 1996. The 38 stations of the Ankang hydrological data acquisition and transmission system including 25 rain gauge stations, eight stage/rain gauge stations and five relay stations are distributed between the Shiquan County and the Ankang City in an area of 12,200 km^2 . It was also put into operation in 1996. All systems mentioned above operate under very good conditions.

According to the analyses of the hydrological forecasting and operation schemes of the system, the average response time of the system is 5 min and 10 s. It takes 3 min, on average, to make a flood forecast. The response speed of the system meets the practical requirement of being less than

10 min. The accuracy of flood forecasting is greater than 90 % and the accuracy in the forecast of heavy floods is greater than 92 % (Huang et al. 2008). To gain an idea about the accuracy of the system's forecasted runoff in 6 h, six heavy floods that occurred after the construction of the reservoir were used to obtain samples of forecasted and observed 6-h runoff values. These samples were used to calculate the errors of forecasted 6-h runoff values. Analyzing this error sample, it was found that the mean of the absolute error, the maximum positive and negative errors are, respectively, 0.787, +66.57, and -57.84 million m^3 . The expected value of 0.0645 mm under the "Forecasted runoff in 6 h (mm)" column of Table 1 was obtained by dividing 0.787 million m^3 by the area of watershed controlled by the Ankang reservoir (12,200 km^2).

3.3 Flood Control Operating Rules

3.3.1 Conventional Operating Rules

The flood control standard of the Xiangyu railway upstream of the reservoir is the control of 100-year flood. Under a 100-year flood, the reservoir's water level cannot exceed 330 m; the flood control standard of the Ankang City downstream is the 20-year flood. If a 5-year flood occurs, the reservoir controls the flood and discharges at a rate of 12,000 m^3/s ; if a 20-year flood occurs, the discharge rate cannot exceed 17,000 m^3/s . The conventional flood operating rules of the reservoir were formulated according to these requirements and are shown in Table 2.

3.3.2 Forecast-Based Flood Control Operating Rules

Based on the analysis of the performance of reservoir regulation and the precision of the forecasts, this study selected the forecasted amount of inflow of the reservoir in 6 h (or runoff in 6 h) as the indicator for assessing flood control operations. The forecasted runoff depth in 6 h instead of 3 h or 12 h was selected as the indicator for the following reasons:

- The hydrological data acquisition and transmission system of the Ankang reservoir is complete. The existing flood forecasting system operates normally. The analysis of the flood forecasting precision of the Ankang reservoir shows that the forecasting precision of 6 h of flood volume is quite high and meets the requirement of operations based on forecasts.
- In the control watershed of the Ankang reservoir, the time for generating runoff after a rainfall event is approximately 6 to 9 h. Moreover, it takes nearly 6 h for the discharged flood flow from the Shiquan reservoir upstream to flow into the Ankang dam site.

Table 2 Conventional flood control operating rules of the Ankang reservoir

Rule No.	Inflow rate (m^3/s)	Water level Z (m)	Discharge (m^3/s)	Remarks
1	$12000 < Q_{in} \leq 15100$	$Z \leq 326$ $Z > 326$	$Q_{out} = 12000$ $Q_{out} = Q_{in}$	Q_{in} and Q_{out} are inflow and discharge respectively
2	$15100 < Q_{in} \leq 17000$	$Z > 326$	$Q_{out} = Q_{in}$	
3	$17000 < Q_{in} \leq 21500$	$326 < Z \leq 328$ $Z > 328$	$Q_{out} = 17000$ $Q_{out} = Q_{in}$	
4	$21500 < Q_{in} \leq 24200$	$Z > 328$	$Q_{out} = Q_{in}$	Inflow reaches the maximum discharge capacity
5	$Q_{in} > 24200$	–	Free discharge	

- According to the analysis of the effects of the flood peak and the flood volume in the Ankang reservoir, 6- to 8-h flood volumes has the most important effect (Liu et al. 2011).

Concrete operating rules based on forecasts were formulated on the basis of repeated analysis, comparisons, and example validations of many different operating rules. The flood control operating rules of the Ankang reservoir based on forecasts were finally determined and are shown in Table 3.

4 Flood Routing Simulation and Uncertainty Analysis Considering Inflow Forecast Errors

4.1 Input of Forecasted Inflows and Their Errors

In order to analyze the response of the flood control system to different series of errors of forecasted inflows, computer simulations were conducted to model the passage of randomly generated flood series. In order to facilitate a reasonable generalization of simulation results, a Gaussian stationary random process was used to represent the error series according to the statistical characteristics of the errors obtained earlier, a random flood inflow hydrograph can be created by superimposing the error series to a representative input flood wave.

Multiple representative flood waves were selected for simulation purposes; the Monte Carlo method was used to generate a number of error series, which are shown in Fig. 3. Among these representative floods, three are most typical and are extensively used for the Ankang reservoir for testing purposes, they are coded as Flood No.197409, 196809 and 198307, shown in Fig. 4. Representative flood and forecast error series were superimposed to generate random inflow series, which are shown in Fig. 5.

4.2 Flood Routing Simulation

Two thousand randomly generated forecast error series were combined to each of the three representative flood series, and flood routing simulations were conducted for a total of six thousand times. All of the simulations start from the cautionary water level, i.e., 325 m of the

Table 3 Forecast-based flood control operating rules for the Ankang reservoir

Rule No.	Runoff in the next 6 h (mm)	Water level Z (m)	Discharge (m ³ /s)	Remarks
1	$R_6 \leq 21$		$Q_{out} = Q_{in}$	R_6 is forecasted runoff in the upcoming 6 h
2	$21 < R_6 \leq 26$	$Z \leq 326$ $Z > 326$	$Q_{out} = 12000$ $Q_{out} = Q_{in}$	Q_{in} and Q_{out} are inflow and discharge respectively
3	$26 < R_6 \leq 29$	$Z > 326$	$Q_{out} = Q_{in}$	
4	$29 < R_6 \leq 36.5$	$326 < Z \leq 328$ $Z > 328$	$Q_{out} = 17000$ $Q_{out} = Q_{in}$	
5	$36.5 < R_6 \leq 40.5$	$Z > 328$	$Q_{out} = Q_{in}$	Inflow reaches the maximum discharge capability
6	$R_6 > 40.5$		Free discharge	

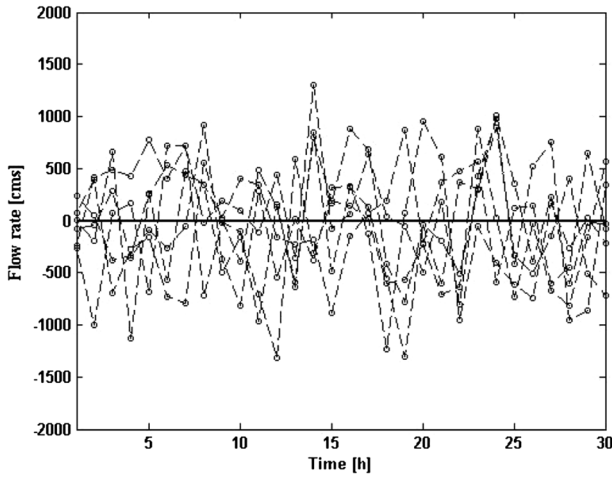


Fig. 3 Error processes of forecasted flood inflows

Ankang reservoir. Taking the heaviest flood occurred since the Ankang reservoir was built (i.e., flood No.198307) as an example, two thousand sets of simulated forecast error series and corresponding inflow series were generated. Considering that many sets of simulations were conducted and it is not necessary to graphically show all the results in one figure, only the first 300 simulation results are shown in Fig. 6.

In Fig. 6, the most important points during the passage of the simulated floods are (1) at the time of 1-h, the inflow is 12,000 m³/s approximately and the initial water level in the reservoir is the cautionary water level of 325 m, (2) at the time of 23-h, the MWL occurs, and (3) at the time of 36-h, the water level declines to approximately 325 m and the flood wave passes through.

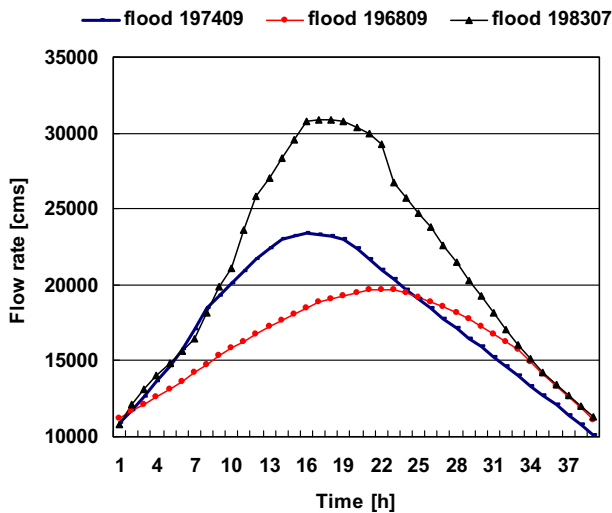


Fig. 4 Three representative flood hydrographs

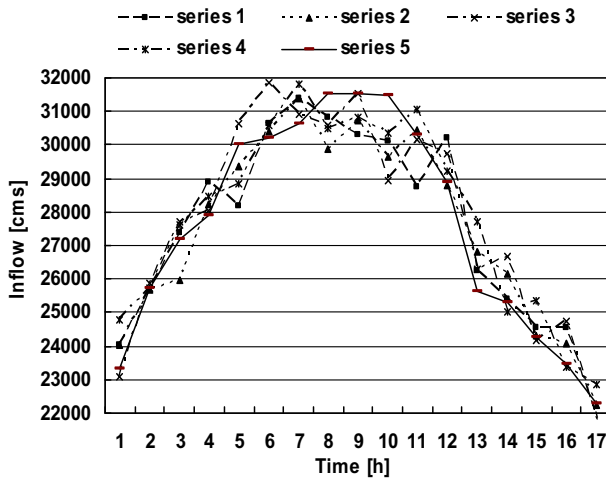


Fig. 5 Randomly generated forecasted inflow

Furthermore, for a specific magnitude of flood, for instance, the 100-year flood, we can also conduct a Monte Carlo simulation by using the following hydrograph magnification method: (1) randomly select one representative flood wave from the three, (2) linearly magnify the selected hydrograph to the magnitude of the 100-year flood, (3) obtain the corresponding 6-h runoff of different lead times based on the magnified hydrograph, i.e., treating the magnified hydrograph as forecasted inflows and use it to set reservoir operation status according to the operating rules at different simulation time steps, (4) generate inflow error series and superimpose it with the magnified hydrograph, and (5) conduct flood routing with the input of the generated inflow series following appropriate operating rules. Using this method, samples of the maximum water levels (MWLs) reached during the passage of the 100- and 10,000-year flood waves can also be obtained. These samples are then used for the determination of the frequency distributions of the MWL reached during the passage of the 100- and 10,000-year flood waves.

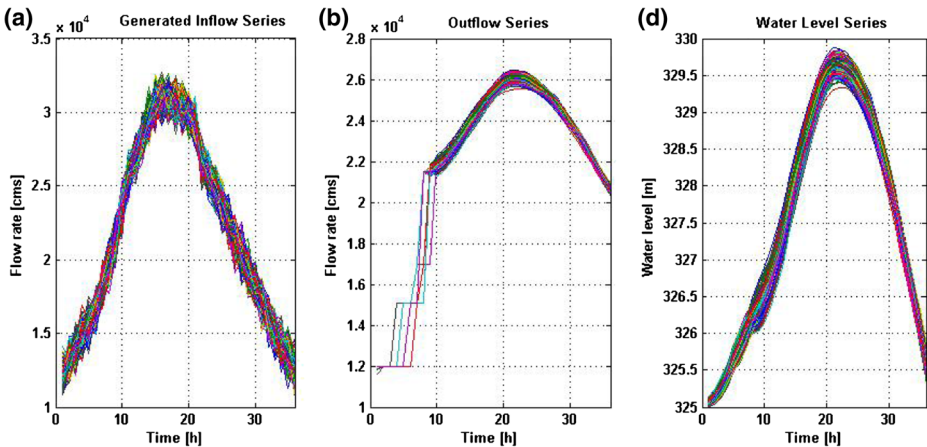


Fig. 6 The first 300 of the 2000 sets of inflow, outflow and water level time series obtained in the simulations taking flood No.198307 as the representative flood

5 Analysis and Discussion

For the three representative flood series, the distribution of the maximum water level (MWL) reached during the passage of a representative flood wave was determined based on the simulation results (Figs. 7, 8 and 9). Afterwards, the statistical characteristics of the output series under the influence of inflow error series were analyzed, the results are what the operators and decision makers interested the most.

From Figs. 7, 8 and 9, it can be seen that the distributions of the maximum water levels are all approximately Gaussian. For simulations taking Flood No.197409 as the representative flood, the mean is 327.81 m and the standard deviation is 0.635 m; for flood No.196809, the mean $\mu=327.84\text{m}$ and the standard deviation $\sigma=0.313\text{m}$; and for Flood 198307, $\mu=329.74\text{mm}$, $\sigma=0.186\text{m}$.

The MWL distributions obtained from the 100- and 10,000-year flood routing simulations were plotted and are shown in Figs. 10 and 11. The mean and standard deviation of the MWL reached during the passage of a flood with a given magnitude can also be obtained from the detailed Monte Carlo simulation results. Assuming that the MWLs resulting from the uncertainties of forecasted inflows are normally distributed, the probability of MWL exceeding a given value during the passage of a flood wave with a specific return period can be estimated. Some of the example results are summarized in Table 4.

For the Ankang reservoir, two stages (i.e., reservoir water levels) of caution are usually paid more attention: (1) if the peak inflow does not exceed that of a 100-year flood, the MWL cannot exceed 330.0 m in the course of flood routing (otherwise, the Xiangyu Railway upstream could be destroyed); (2) the MWL cannot exceed 337.33 m (otherwise the dam may be destroyed) in the occurrence of a design flood (1000-year) or a check flood (10,000-year). There are no more restrictions on discharge rates from the reservoir for downstream protection targets when floods occur with return periods of 20 years or longer. The probabilities of reaching these stages of caution with forecast-based reservoir operation during the passage of floods of various return periods can also be calculated based on the assumed normal distributions for MWLs and their means and standard deviations. These probabilities are also

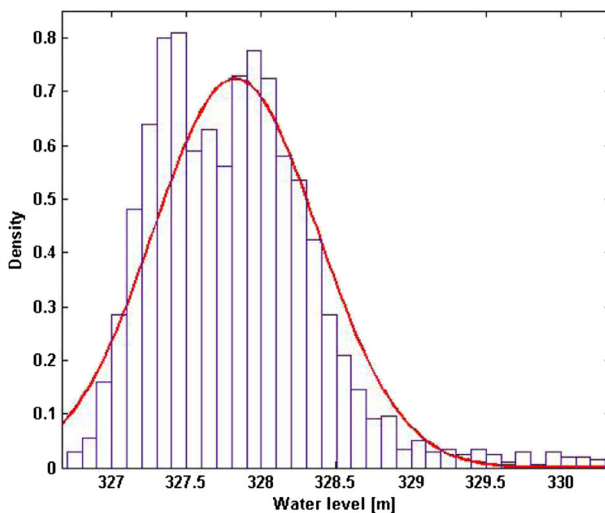


Fig. 7 The distribution of the MWL reached during the passage of Flood 197409

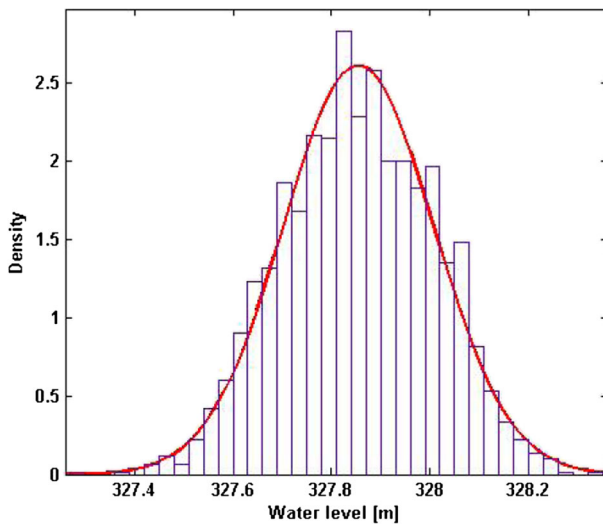


Fig. 8 The distribution of the MWL reached during the passage of Flood 196809

reported in Table 4 and can be used to compare with similar probabilities expected if the reservoir is operated in a conventional way.

The conventional way of flood regulation of reservoirs which depends only on observed inflows also involves uncertainties and would also result in risks of exceeding specified MWLs, because there are always differences between the measured inflows and actual inflows due to measurement errors. These uncertainties and risks are unavoidable and are very difficult to deal with although they could be significantly reduced by improving the accuracy of measurements. Since the risks resulting from the conventional way of reservoir flood control operation cannot be quantified, we could not compare directly the forecast-based flood control with the conventional way of flood control based on the risks associated with each of them. What we can see from the above simulation results for

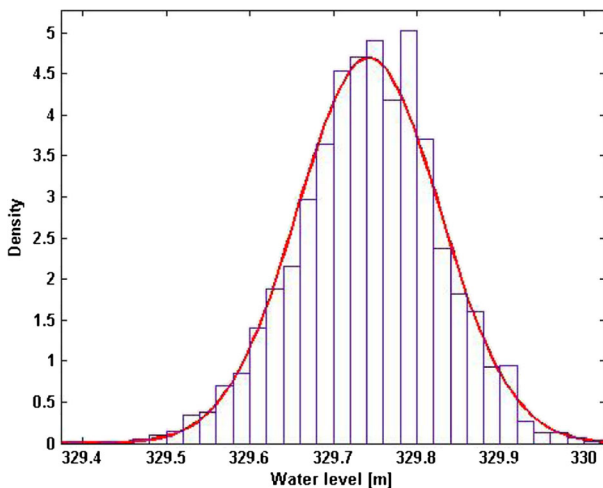


Fig. 9 The distribution of the MWL reached during the passage of Flood 198307

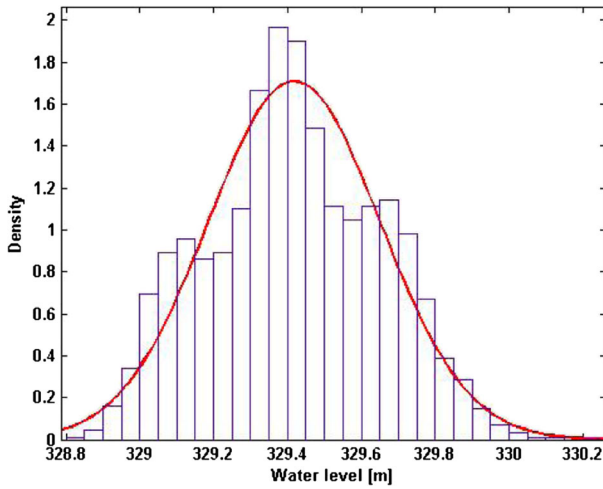


Fig. 10 The MWL distribution for 100-year flood

forecast-based flood control is that the risks associated with the forecast-based operation for the Ankang reservoir are very small and are within an acceptable level for current conditions.

The above analysis also quantifies the uncertainty of the MWL that may be reached in flood control based on forecasted information if a flood with a specific return period occurs. According to the simulation results, surprisingly, the standard deviations of the MWLs decreased with the increase of the flood peak, i.e., the distribution of the MWLs tend to be more concentrated for larger floods than for smaller ones. This may have been caused partly by the selection of multiple representative floods in the simulation, for small floods, the MWL is more sensitive to the difference of representative flood hydrographs, but for an extremely large flood, it is no longer the case, instead, the MWL is controlled by the flood peak itself rather than the shapes of the representative flood hydrographs.

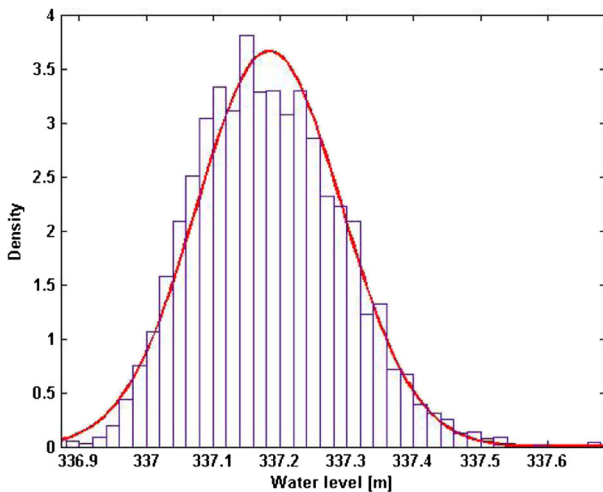


Fig. 11 The MWL distribution for 10,000-year

Table 4 Uncertainties in flood regulations based on inflow forecasts for the Ankang Reservoir

Flood return period (yrs)	20		100		1000		10,000	
Moments of MWL distribution (m)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
	328.2	0.254	329.42	0.233	333.14	0.188	337.184	0.109
Probability of MWL exceeding 330.0 m	≈0		≈0.0065		≈1.0		≈1.0	
Probability of MWL exceeding 333.0 m	≈0		≈0		≈0.7718		≈1.0	
Probability of MWL exceeding 337.33 m	≈0		≈0		≈0		≈0.093	

6 Conclusions

For reservoir flood control based on forecasts, the forecast errors and the possible magnitudes of incoming floods are two different manifestations of uncertainty, but their essence is the same, namely the mismatch between forecasted inflows and actual inflows that occurred later on. Taking the Ankang reservoir as a case study, this research captured the essence of this uncertainty in reservoir flood regulations, focused on inflow forecast errors and analyzed the water level uncertainties resulting from forecast errors in flood routing. Generally, forecast-based flood operating rules proposed in this paper can serve as an example for effective reservoir operation and water resources management, the proposed uncertainty analysis method may be used for similar problems of reservoir flood control.

The statistical characteristics of the forecast inflow error series were of great significance and their results affected significantly the probabilities of reaching the various stages of caution. The absolute value of the forecast error generally increases as the flow rate increases. Strictly speaking, the forecast inflow error series is not a stationary process. However, analysis indicated that the forecast error series approximately follow normal distributions with zero means at all the lead times of interest. As the flow rate increases, the standard deviation of the forecast error series also increases. However, when the inflow rate is high (greater than 12,000 m³/s), the first two moments of the forecast error series at all the lead times of interest are roughly the same and are very close to each other. When the inflow rate is not in this range, historically measured data are too few and are not sufficient for analysis and inference. Therefore, the part exceeding this range needs to be studied further. These findings may also be valid for other watersheds and river systems.

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